# Two Tank Indirect Thermal Storage System

## Parametric Studies for FLABEG Solar International GmbH and Solar Millennium AG

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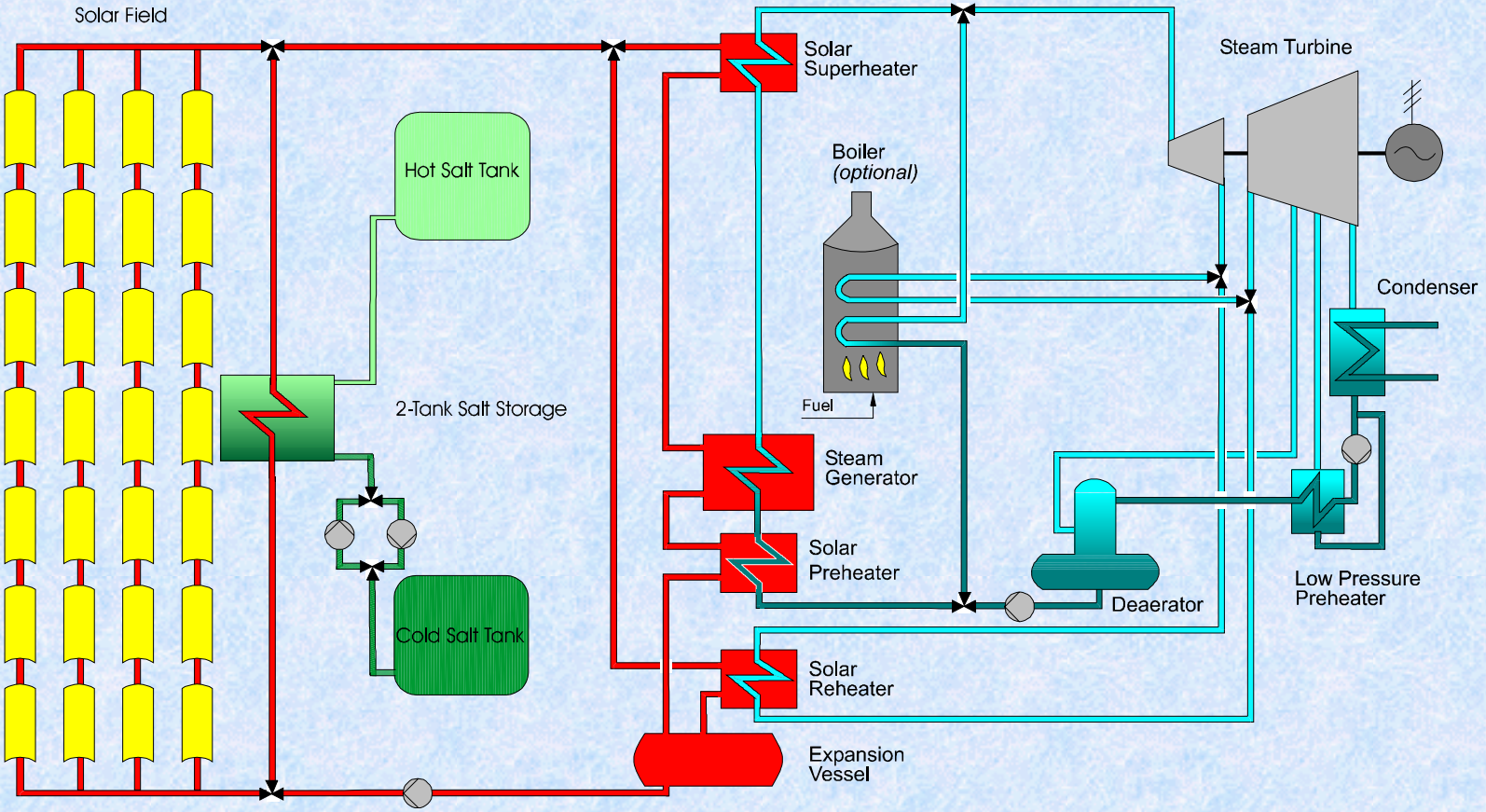
# Indirect Nitrate Salt Thermal Storage



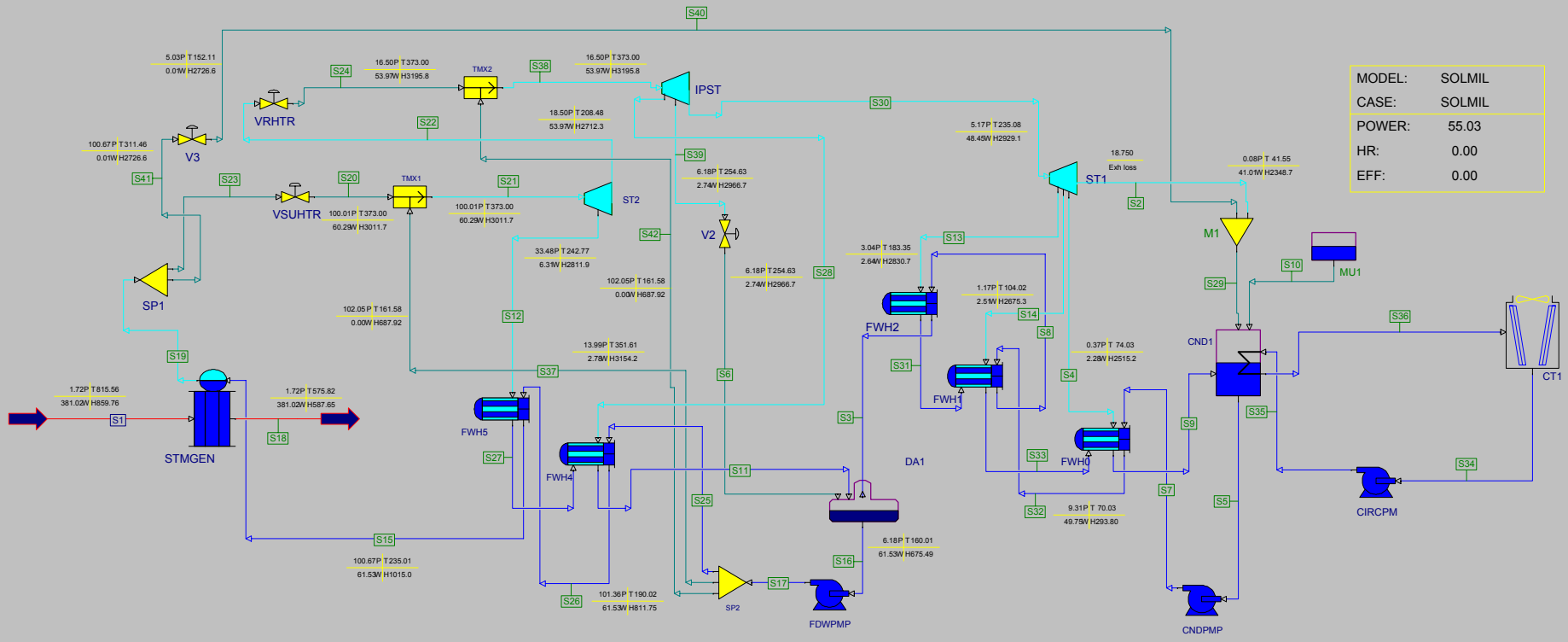
# Parametric Studies

- Select oil-to-salt heat exchanger approach temperature which provides lowest levelized energy cost
- Analysis of oil-to-salt heat exchanger (exchange area, pressure losses, and cost), storage inventory temperatures (nitrate salt volume, tank dimensions, and costs), part load steam generator performance (Therminol temperature distribution, and live/reheat steam temperatures), part load Rankine cycle performance (live/reheat steam pressures, and cycle efficiency), and annual plant electric output

# Rankine Cycle

- Generator output of 55 MWe
- Single reheat cycle with 6 feedwater heaters
- 100 bar / 373 ºC live steam
- 16.5 bar / 373 ºC reheat steam
- Final feedwater temperature of 235 ºC
- Condenser pressure of 90 millibar
- Gross cycle efficiency of 0.375

# GateCycle Rankine Cycle Model



# Steam Generator Model

Inputs from GateCycle analysis

- Feedwater flow rate
- Live steam flow rate
- Cold reheat steam flow rate and temperature

# Steam Generator Model (Continued)

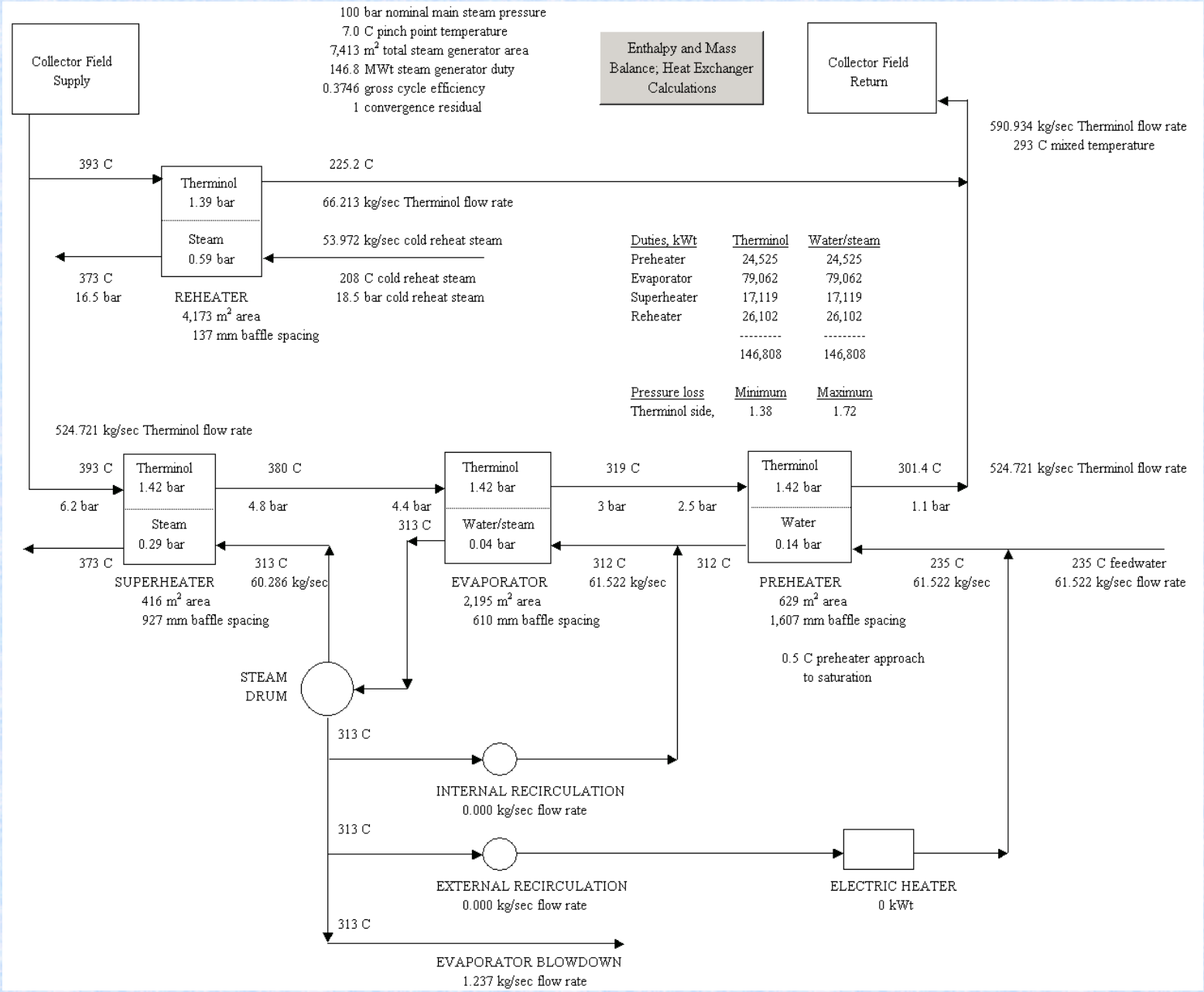
Iterate on Therminol flow rate and inlet/outlet temperatures for each heat exchanger, subject to following constraints:

- Nitrate salt duty equals water/steam duty
- Reheater Therminol outlet temperature equals 225.2 ºC
- Adjust evaporator pinch point temperature to give preheater Therminol outlet temperature of 301.4 ºC

# Steam Generator Model (Continued)

- Select trial water/steam and Therminol velocities
- Calculate inside and outside heat transfer coefficients, overall heat transfer coefficient, log mean temperature difference, and heat exchange area
- Calculate number of tubes, length of tubes, and baffle spacing
- Iterate on tube side velocities and baffle spacing to meet pressure loss constraints

# Steam Generator Model (Continued)



# Oil-to-Salt Heat Exchanger Model

- Select trial nitrate salt (shell side) and Therminol (tube side) fluid velocities
- Calculate inside and outside heat transfer coefficients, overall heat transfer coefficient, log mean temperature difference, and heat exchange area
- Calculate number of tubes, length of tubes, and Therminol pressure losses, and nitrate salt pressure losses

# Oil-to-Salt Heat Exchanger (Continued)

- Iterate on number of heat exchangers and tube length to meet pressure loss constraints
- Design philosophies
  - Thermal storage discharging duty: 124.1 MWt to 135.2 MWt part load steam generator duty
  - Thermal storage charging duty: 146.8 MWt full load steam generator duty, or 124.1 MWt to 135.2 MWt part load steam generator duty

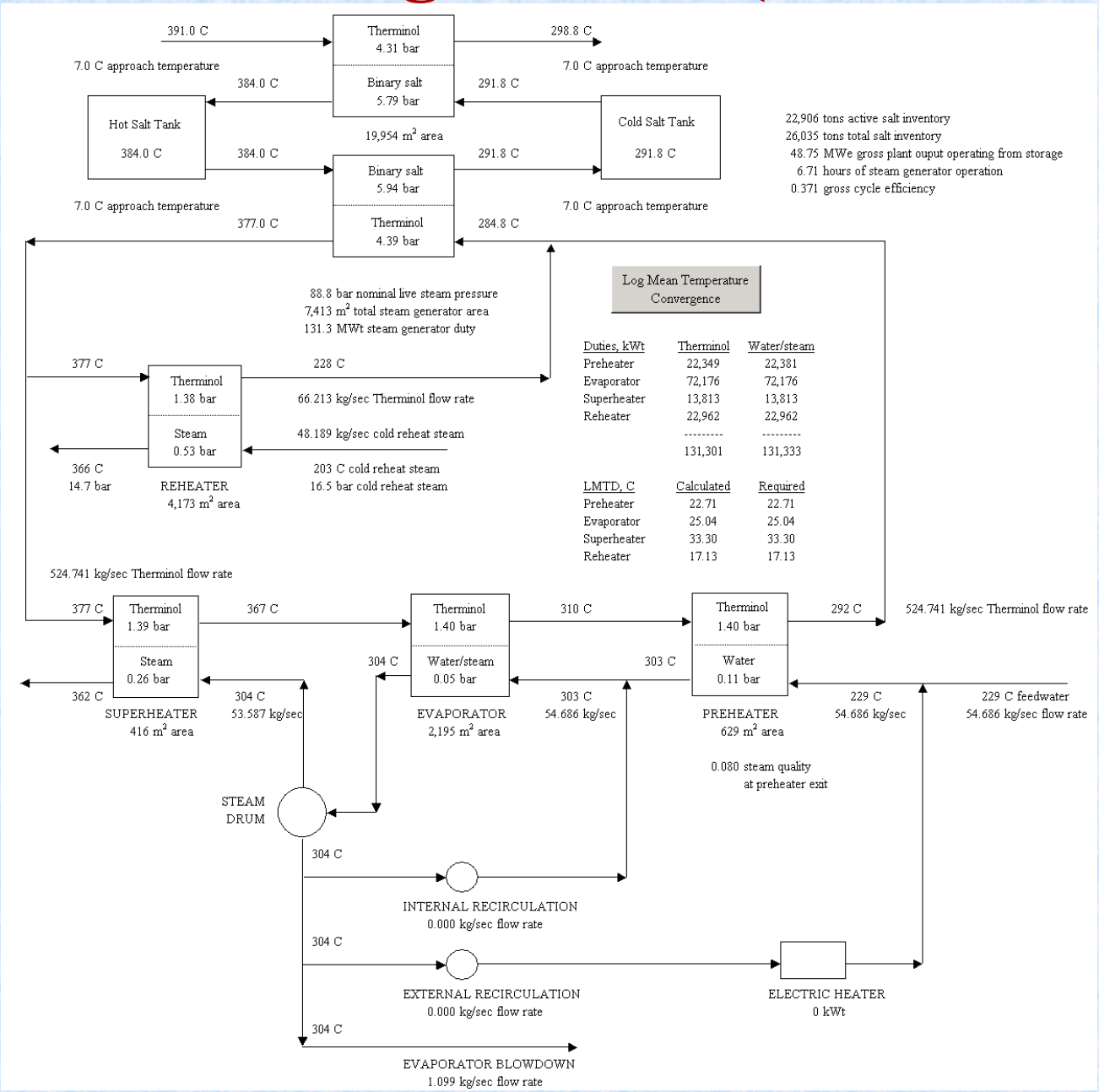
# Oil-to-Salt Heat Exchanger (Continued)

| Approach Temperature, ºC | Heat transfer area, $m^2$ | Number of exchangers |
|---|---|---|
| 5 | 36,390 | 8 |
| 6 | 28,566 | 8 |
| 7 | 22,827 | 6 |
| 8 | 19,187 | 6 |
| 9 | 16,529 | 5 |
| 10 | 16,197 | 4 |
| 11 | 12,761 | 4 |

# Thermal Storage Model

- Two approach temperatures on oil-to-salt heat exchanger cause Therminol supply temperature to steam generator to be 12 ºC to 24 ºC below design value of 373 ºC
- With Therminol flow rate to the steam generator fixed at the design value, thermal input is 84 to 92 percent of design
- Oil-to-salt heat exchanger, steam generator, and Rankine cycle all operate at part load during thermal storage discharge

# Thermal Storage Model (Continued)



# Thermal Storage Model (Continued)

- Trial Therminol, water, and steam temperatures for superheater - evaporator - preheater combination are selected, from which the log mean temperature difference for each shell is calculated
- Trial Therminol outlet temperature for reheater is selected
- Thermal duties on the water and steam sides of four heat exchangers are calculated

# Thermal Storage Model (Continued)

- Therminol flow rates through the reheater and the superheater - evaporator - preheater combination are calculated based on trial temperature distribution and thermal duties
- Therminol flow rate through the reheater is fixed at the design flow rate
- Tube side, shell side, and overall heat transfer coefficients were calculated for four heat exchangers

# Thermal Storage Model (Continued)

- Required log mean temperature difference for each shell is calculated, using the thermal duties on the water and steam sides and the overall heat transfer coefficients:

$$\text{Required log mean temperature difference, } {}^{o}C = \frac{Q,\ kJ/sec}{(U_{overall},\ kJ/m^2\ -{}^{o}C)(Area, m^2)}$$

- Calculated log mean temperature difference is developed using standard formula:

$$\frac{\text{Greater temperature difference, } {}^{o}C - \text{Lesser temperature difference, } {}^{o}C}{ln\left[\frac{\text{Greater temperature difference, } {}^{o}C}{\text{Lesser temperature difference, } {}^{o}C}\right]}$$

# Thermal Storage Model (Continued)

- Required and calculated values are compared; if the values differed, a new trial Therminol temperature distribution is selected, and the process repeated until the log mean temperature differences converged

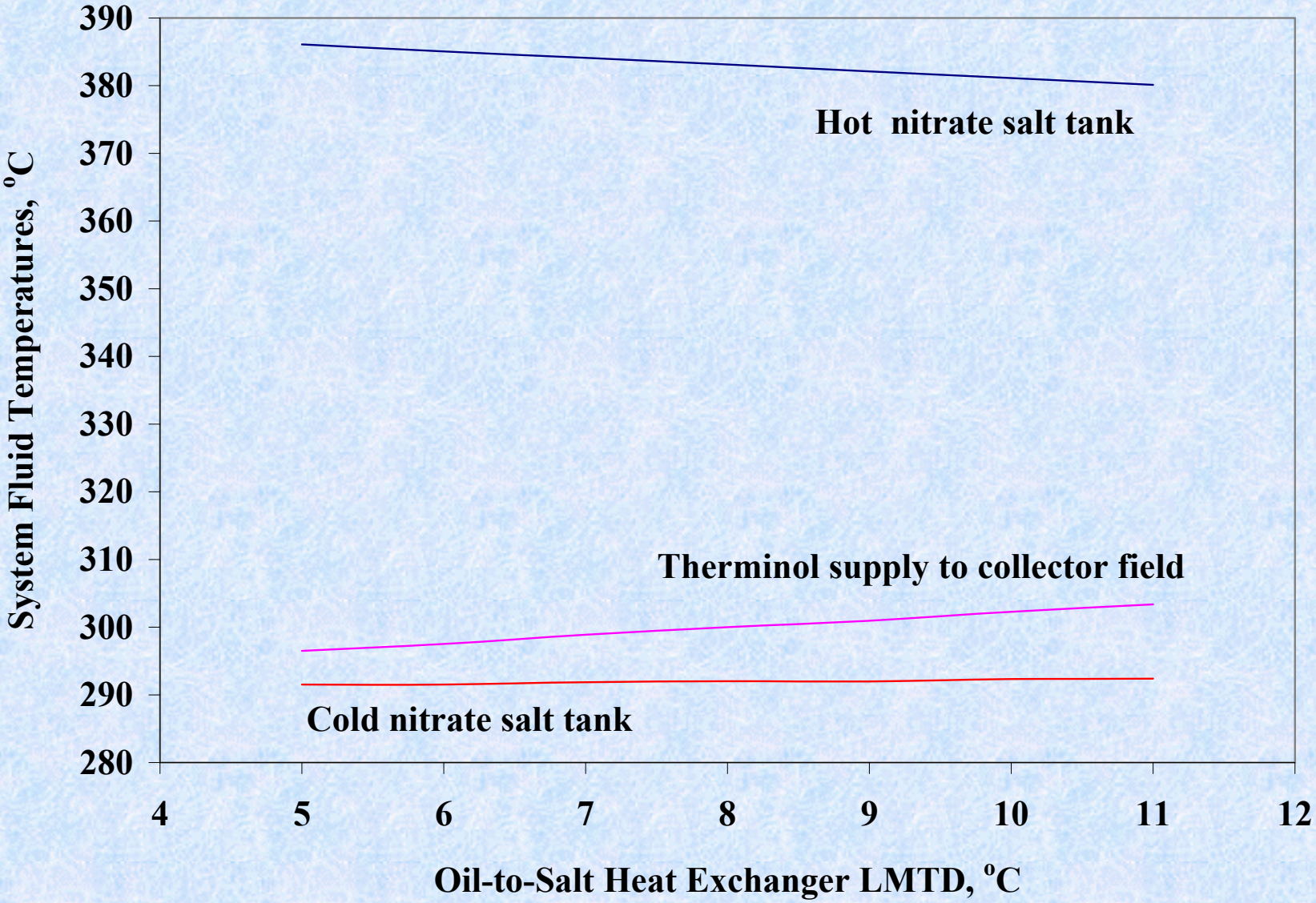
- Resulting values for live steam temperature, live steam flow rate, reheat steam temperature, and reheat steam flow rate are exported to the GateCycle program

# Thermal Storage Model (Continued)

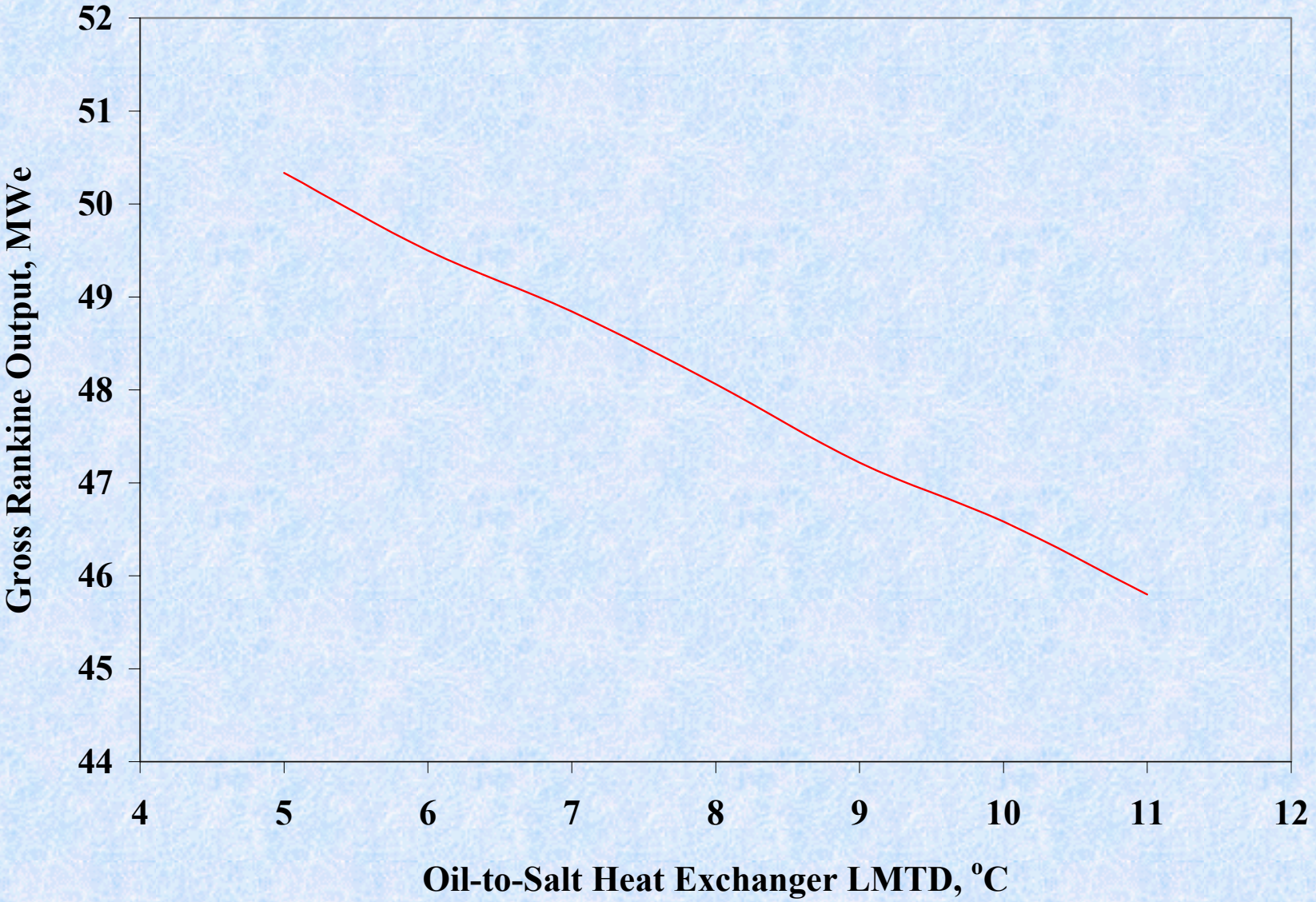
- In GateCycle, live steam pressure is determined by the steam flow rate through the turbine. GateCycle calculates live steam pressure, condenser pressure, final feedwater temperature, and gross generator output, and exports these values back to the part load steam generator model

- Iterations are repeated until constant values for live and reheat steam pressure and temperature, and final feedwater temperature are obtained

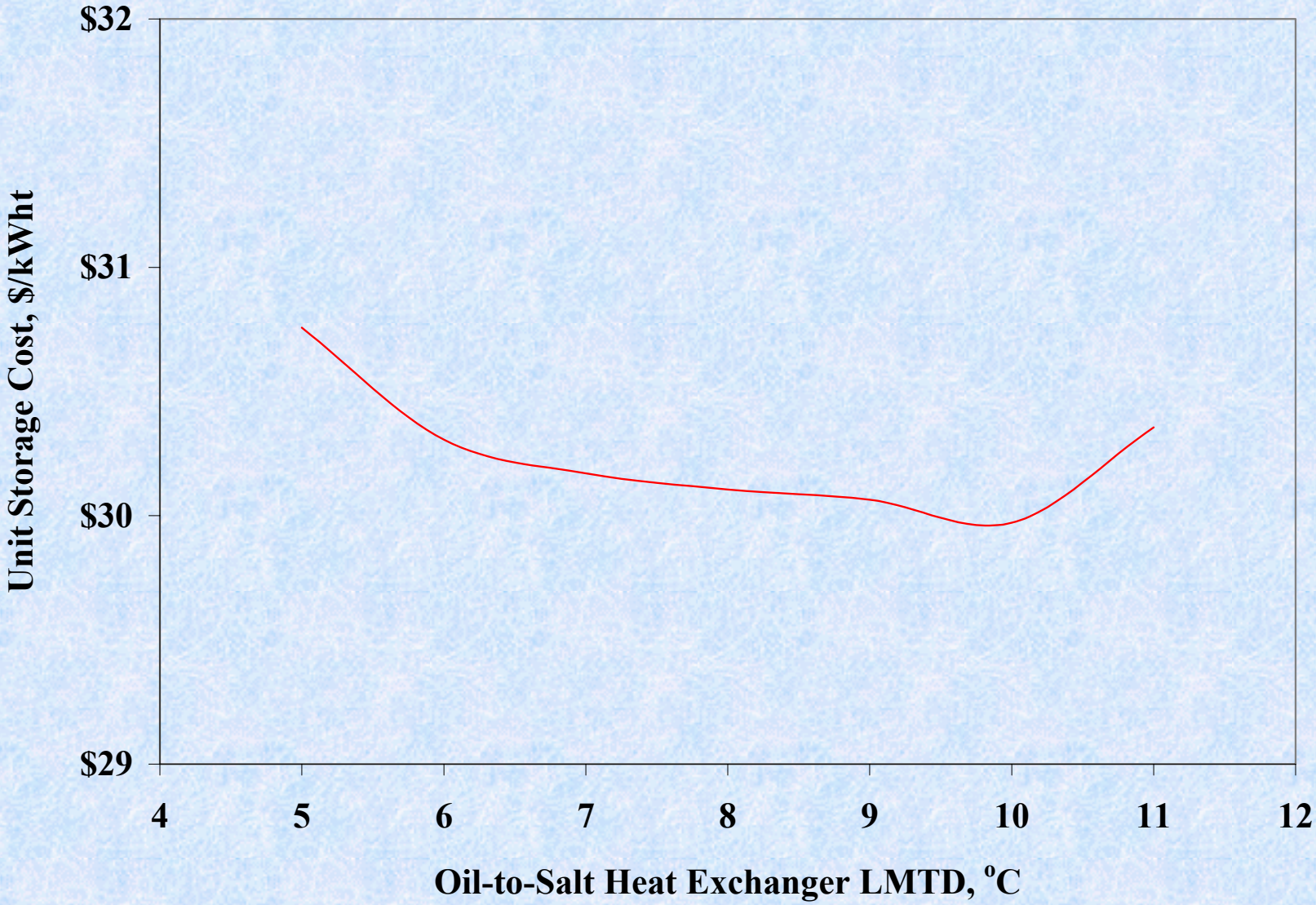
# System Fluid Temperatures



# Rankine Cycle Output



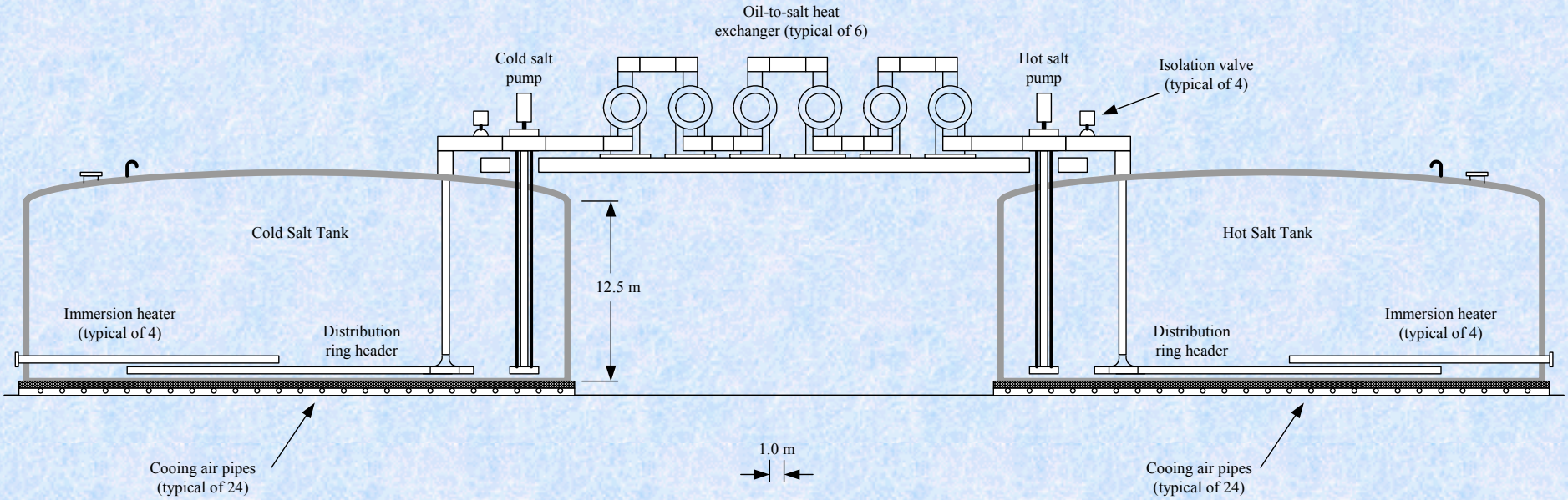
# Unit Thermal Storage System Costs



# Optimum Design Parameters

- Oil-to-salt heat exchanger approach temperature of 7 ºC
- Oil-to-salt heat exchanger design duty during thermal storage discharging equal to part load steam generator duty of 131.3 MWt (90 percent of design steam generator duty)

# Equipment Arrangement



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